ABSTRACT

This thesis was intended to analyse diagnostic metods for carbon fibre reinforced polymer (CFRP) structures with imperfections in order to explore the possible application of these materials in industry. The analysed structures have imperfections understood as voids, gaps between fibre bundles, delaminations, holes, etc. or inclusions in the form of embedded optical fibres with fibre Bragg grating (FBG) sensors. Such imperfections can be related to the manufacturing method features (e.g. voids in additive manufactured (AM) structure) or inclusions introduced intentionally (e.g. optical fibres) or the geometric characteristics of the structure (e.g. holes). All of the elements result in local stress/strain concentration, and changes in material mechanical and material properties that influence their degradation processes

The first part of this thesis aimed to determine the thermo-mechanic characteristics of CFRP samples with embedded FBG sensors fabricated by green method of manufacturing, 3D printing. Additionally, the influence of embedded FBG sensors on the mechanical strength of CFRP material was evaluated based on the tensile test results. This section included both numerical and experimental investigations. The second section was the investigation of the effect of drilling two holes in different configurations on the mechanical behaviour of plain weave composite structures. This part was mostly experimental, though a numerical analysis was also conducted for verification of the numerical model utility. The final part, which was a comparative study, was devoted to studying the application of machine learning (ML) algorithms on the prediction of the degradation process of the plain weave composites with different stacking sequences and two interacting holes.

A novelty in AM structures with embedded FBG sensors is related to the embedding process and application of the sensors for strain measurements of elements subjected to thermal and mechanical loading. Numerical simulation was conducted inside ABAQUS finite element method (FEM) software to complement numerous experimental investigations to verify the computational results for the samples under thermal loading. The numerical works results were in good agreement with the outcomes given by FBG sensors. Embedded FBG sensors were able to identify thermal strain accurately for additively manufactured composite structures. Additionally, the tensile test was performed on the samples exposed to elevated and sub-zero temperatures. The aim of the test was to determine the influence of embedded optical fibres on mechanical strength of the CFRP material. FBG sensors were also applied for strain measurements during the test. The achieved results were compared to strain values determined by the tensile machine with a good agreement between the methods. This AM method can be applied for fabrication elements with embedded FBG sensors also using the other fibre reinforcement material. Additionally, FBG sensors can be used for strain measurements during both thermal and mechanical loadings.

Plain weave composite is a long-lasting type of fabric composite that is stable enough when being handled. On the other hand, composite laminates with notches have been employed in various industrial applications, e.g., swash plates, adaptor plates, and repair patches. These holes reduce the structural integrity of the composite structures. In woven composite laminate with two interacting circular cut-outs, the hole configurations influences the strength and stress concentration factor (SCF) of that structure. Drilling one notch in the loading direction improved the structural behavior of plain-weave composite structures as also observed by the SCF analysis through FEM. The main aim is to investigate, experimentally and numerically, the interaction between two notches in different configurations while the composite laminate was under tension. The location of the processing zone (the location of failure initiation) depends upon the orientation of the holes. The characteristic distance and processing zone for each specimen were identified for each sample integrating the FEM and Digital Image Correlation (DIC) method. Point stress criterion (PSC) and Extended-PSC (EPSC) approaches were employed to predict the failure strength of each specimen. The failure initiation and progression with through the interaction between two notches was studied via infrared thermography (IRT). Furthermore, IRT results were complemented through fractographic analysis and the type of fracture for each sample was discussed in detail.

Finally, composites with hole/s have been extensively employed in industry, though they have weak structural performance and complex design processes. Numerous number of geometry/material parameters have been used for designing composites with holes. Thus, an efficient computational tool is essential for prediction of the structures. Various ML approaches were developed to achieve the model with highest accuracy taking into account the maximum tensile stress of composite plates with two interacting holes. Also, the effectiveness of each technique was discussed. FEM simulations were performed through ABAQUS software integrating with the python macro code to provide a data-rich framework (8960 data). The predictions obtained through ML methods were compared with those extracted by the FEM simulations. An evolutionary algorithm (TPOT) and automatic neural network search (AuoKeras) were employed for predicting the tensile stress appeared in the vicinity of the holes. An automatic grid search method was employed to choose the most efficient method capable of predicting the material attribute target values (maximum stress) for different tests. Stacked model did provide the most accurate predictions among other techniques. The applicability of stacked algorithm in other composite materials was discussed.

Following an introductory chapter and a review of the state-of-the-art (Chapters 1-2), I am discussing my contribution to the field in Chapters 3-5, which consists of:

- determination of the possibility of embedding FBG sensors into CFRP samples fabricated using additive manufacturing technique – FDM
- determination of the diagnostic method for CFRP structures based on embedded FBG sensors including the analyses of the influence of the embedded optical fibres on the mechanical strength of the samples
- development of a numerical model of FRP structure with holes under loading
- application of theoretical models for strength prediction of woven structures with holes
- analysis of the degradation processes of FRP structures (AM with embedded FBG sensors and woven with holes) and determination of the dominant type (matrix cracking, fibre breaking, etc.)
- developing a novel method to accurately predict the maximum tensile stress of the woven composites with interacting holes under tension

The summary, conclusion, and future works required for further development of this thesis are discussed thoroughly in Chapter 6.

The results of the performed analyses can be also extended to the other types of fibre reinforcement used in FRP elements.